

WATERMELON RIND–BIOPOLYMER AS A SUSTAINABLE MEMBRANE FOR TARGETED VEHICLE EMISSION REDUCTION

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ABSTRACT. The development of efficient carbon capture solutions is necessary because the burning of gas and petroleum has caused a rapid increase in atmospheric CO₂, exacerbating climate change. Membrane-based CO₂ separation has become a feasible path to carbon neutrality in the energy and industrial sectors. Polymeric membranes have benefits like low cost, processability, and mechanical flexibility compared with metallic and ceramic inorganic membranes, which offer superior selectivity and thermal durability. In this project, watermelon rind, which is rich in cellulose and pectin, was processed into a biodegradable membrane. The extracted biopolymers were blended and cast into thin films to form an eco-friendly material with desirable mechanical and adsorption properties. The final membrane exhibited a uniform structure, stable water flow, and strong pollutant absorption ability. This paper reviews the comparative studies between membranes with and without PVA, which revealed that PVA acts as an effective polymeric binder, improving the structural integrity and pollutant adsorption capacity. The developed membrane demonstrated up to 85% reduction in CO₂, NO_x, and Sulfur pollutants, with a notable decrease in CO₂ concentration. Also, the stability and effective adsorption of the membrane were confirmed by analyzing the functional groups, surface morphology, and crystalline structure using FTIR, SEM, and XRD Analysis.

KEY WORDS: Vehicle emissions, Biodegradable organic membrane, Adsorption capacity, Emission flux modeling, Real-time

INTRODUCTION

One major source of greenhouse gas and air pollution emissions is road transportation. Specifically, CO₂ emissions from vehicles are pivotal for global carbon trends, while other pollutants, e.g., NO_x, PM, and CO, are critical for urban air quality and human health. This highlights the importance of modeling carbon flux, including the rate of carbon emissions from vehicles, in climate and air pollution policy. Several scholars have proposed frameworks and models for assessing CO₂ emission factors (mass of CO₂ per distance and vehicle) under actual driving conditions [1]. Established measurement models of CO₂ emission factors for passenger vehicles, applying a microscopic traffic simulation (PTV Viscum) and the moves emission simulation model. They considered road structure segment lengths and traffic demand volume, intersection flow, and formed functional relationships, in particular, a double exponential function between those factors and CO₂ emission factors [2]. Similarly, in real heterogeneous traffic conditions, a carbon emission factor model was developed based on Fick's second law of diffusion and the law of mass conservation. They then associated the diffusion flux gradients in the x-, y-, and z-directions to the emission factor under different road-environment assumptions, open, semi-enclosed, and enclosed, to show how spatial dispersal and vertical wind speed impacted the emission factor. High-resolution emission inventories that leverage real-world traffic data have been established at larger spatial scales [3]. For instance, used detailed traffic data like speed and fleet composition to make EMBEV-Link, a link-level emission factor model of the Beijing Road

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network, which described spatial and temporal patterns of emissions of CO₂, NO_x, and PM_{2.5}. Methodologically, there has been a growing interest in surrogate modeling and data-driven emissions models, machine learning [4]. Neural move is a light-weight neural network-based surrogate model for the moves model, specifically focused on estimating CO₂ emissions. These surrogate models provide efficient estimations of carbon flux from transportation modes as they can provide estimates with low computational expense, allowing real-time and/or microscopic (i.e., vehicular scale) estimation of carbon flux from transportation. Analytical models can also be leveraged in the realms of policy-making and planning, notably in linking vehicle kilometers traveled (VKT) with carbon emissions. For example, an analytical model measured CO₂ emissions based on different delivery and personal-travel scenarios, and evaluated several key quantifiable parameters, such as customer density and emission ratios, to indicate when carbon emissions from delivery via trucks based on VKT are more carbon efficient than personal vehicles. In summary, broader scrutiny of vehicle emission factors shows complexity and variability in modeling approaches [5]. For example, assessed traffic-simulation-emission modeling approaches and noted, "Reliance on one or two vehicle types, driving cycles, fleet variability, and pollutant speciation cannot be overlooked" when developing reliable emissions estimates.

EXPERIMENTAL

Materials and chemicals

Fresh watermelon rind, mainly the white inner part, was taken as the initial raw material for biopolymer extraction. Distilled water was the solvent medium throughout the experiment. Ethanol (70%) was used to precipitate the biopolymer obtained. To make the membranes more flexible, a plasticizer, either glycerol or sorbitol, was used. Sodium alginate (0.1, 1 wt%) acted as a thickener and a cross-linker. pH adjustment was done using sodium hydroxide (NaOH) and hydrochloric acid (HCl). Polyvinyl alcohol (PVA) was a film-forming polymer. The equipment used was a grinder, an 80 mesh sieve, a tray dryer, a magnetic stirrer, glass casting plates, Petri dishes, and a vacuum desiccator.

Preparation of watermelon rind powder

The rinds of fresh watermelon (*Citrullus lanatus*) were gathered from a nearby fruit market and carefully cleaned using distilled water to eliminate any dirt or contaminants that might have adhered. Figure 1 shows that, after carefully separating the inner red pulp from the outer green layer, the white rind portion was cut into tiny pieces. The cleaned rind samples were ground into a fine powder using a laboratory grinder and then sieved through an 80-mesh screen after being oven-dried for 24 hours at 55 ± 2 °C until a consistent weight was achieved. 1,000 ml of distilled water was used to suspend 50 grams of powdered rind, solid: liquid = 1: 20 w/v. After acidifying the suspension with 1 N HCl to a pH of 2.0, it was heated to 80 °C for 90 minutes while being continuously stirred. After the extract had cooled at room temperature, it was filtered, and two volumes of 95% ethanol were added to precipitate the pectin, following established procedures for pectin isolation [6]. A 500 mL round-bottom flask with 450 mL of 1.0 M acetic acid and 15 g of powdered watermelon rind was kept at a solid to liquid ratio of 1: 30 (w/v). Sodium hydroxide solution was used to bring the mixture's pH within the range of 1.0 to 5.0. The suspension was continuously stirred for 50-110 minutes after being heated to the appropriate extraction temperature, 60-120 °C. The hot mixture was filtered using a double-layered muslin cloth, after extraction in order to separate the liquid extract from the solid residue. Ethanol was then added to the filtrate at a ratio of 2: 1 (ethanol: extract), and the mixture was stirred for 10 min before being left to stand overnight to allow complete pectin coagulation [7]. The precipitated pectin was rinsed three times with 70% (v/v) ethanol after being filtered through a double-layer muslin cloth to

remove any last impurities and low-molecular-weight soluble substances. Following washing, first, the material was dried in a vacuum oven at 45° C for 24 hours. Then it was allowed to cool down to room temperature, ground to a fine powder, and finally, packed in airtight and moisture-proof containers for further use in film preparation and characterization [8].

Pectin yield

The equation below was used to calculate the amount of pectin yield from watermelon rind on a dry weight basis.

$$\text{Pectin Yield (\%)} = (\text{Weight of extracted pectin} / \text{Initial weight of raw material}) \times 100.$$

The dried watermelon rind was gathered during the sample preparation phase, and the dried pectin was produced by a sequence of procedures including filtration, precipitation, and drying [9].



Figure 1. Preparation of watermelon rind powder through cleaning, drying, grinding, and sieving.

Pre-treatment of watermelon rind powder

An alkaline pre-treatment was used to remove lignin, hemicellulose, and other non-cellulosic materials from the watermelon rind powder, as well as to increase the cellulose content. Basically, 10 g of powder obtained from the rind was mixed with 100 ml of 0.3 wt% sodium hydroxide (NaOH) solution. The mixture was stirred continuously at 50 °C for 30 minutes to allow the lignin dissolution and alkali-soluble impurities. After the process, the slurry was filtered and washed with distilled water several times until it had a neutral pH. To set the cellulose framework and also to neutralize any alkali left, the treated residue was washed with 1 wt% dilute acetic acid. The material was washed with distilled water again, and then it was dried in a hot, air oven at 50 °C until it was of a constant weight [10].

Preparation of watermelon rind slurry and preparation of polyvinyl alcohol (PVA) solution

The dried and pre, treated rind powder (Figure 2) that was converted into a uniform slurry by dispersing it in distilled water at a weight, to, volume (w/v) ratio of 1:10. The dispersion was done gradually with continuous stirring to avoid lumps and to ensure homogeneous mixing of the solid particles. After that, glycerol was added to the slurry at 20 and 30 wt% concentrations, based on the dry weight of the rind powder, and it was employed as a plasticizer to make the membrane more flexible and to decrease the hardness. The mixture was heated to 60° C, and it was kept at this temperature with the stirring being continued for about 20 min. Their heating and stirring helped the uniform dispersion of the rind particles, facilitated the incorporation of glycerol, and promoted the effective interaction of the biopolymeric constituents present in the rind powder. Upon completion of the heating time, the slurry exhibited a smooth and consistent texture, thus indicating sufficient homogenization, and it was allowed to cool somewhat before proceeding or mixing with the polymer solution for membrane fabrication [11]. To serve as the polymer matrix

base for the blending process, an aqueous polyvinyl alcohol (PVA) solution was prepared. Firstly, 5 g of PVA powder was slowly added to 100 ml of distilled water in a glass beaker to avoid the creation of agglomerates [12]. The mixture was brought to 80,90 °C with the help of a magnetic stirrer, which was also used for the continuous stirring of the mixture to ensure even heating and good polymer dissolution. The heating was prolonged until the mixture became clear, transparent, and viscous, which indicated that the PVA chains were fully hydrated and dissolved. Boiling and a lot of water evaporation were avoided during the operation. After the complete dissolution, after the heating source was turned off, the PVA solution was allowed to cool to room temperature naturally by being exposed to the open air. Then the cooled solution was stored in a tightly closed container to prevent contamination and evaporation until it was mixed or used for membrane fabrication. The choice of glycerol concentration, which included 20% and 30% w/w, is based on previous observations from literature on the range of optimal glycerol concentrations for biopolymer plasticization of membranes consisting of cellulose- and pectin-based materials. Lower glycerol concentrations are insufficient for plasticization and result in brittle membranes, whereas high concentrations lead to swelling and weak membranes. As observed in the current study, the addition of 20% glycerol optimized both flexibility and stability of the membranes, while increasing the concentration of glycerol to 30% further improved chain mobility and resulted in free volume formation within the polymeric chains. Increased free volume contributes to enhanced gas permeability but may negatively affect the tensile strength of membranes as a result of reduced intermolecular interaction.



Figure 2. Preparation of membrane components: (a) watermelon rind slurry and (b) PVA solution.

Blending, membrane casting, and preparation of a homogeneous slurry

The bio waste and PVA solution were mixed in volume ratios of two, i.e., 1:1 and 2:1. (In Figures 3a and 3 b) The parameters that helped to determine the blending ratio were the mechanical strength, flexibility, and structural stability of the membrane. The blending was done by using a magnetic stirrer for a continuous 30 minutes or so to facilitate the complete homogenization of the biopolymeric components and to get a uniform, bubble-free casting solution. The speed of the stirrer was kept moderate so as not to allow air to be entrapped during stirring. The resulting blend after homogenization was a prepared watermelon rind slurry and polyvinyl alcohol (PVA) solution, which were blended in volume ratios of 1:1 and 2:1, depending on the targeted mechanical strength, flexibility, and structural stability of the final membrane. The blending process was carried out under continuous magnetic stirring for approximately 30 minutes to ensure complete homogenization of the biopolymeric components and to obtain a uniform, bubble-free casting solution. Care was taken to maintain moderate stirring speeds to prevent air entrapment during mixing, poured onto a clean, leveled glass plate or Petri dish [13]. The solution was then evenly spread by using a doctor blade or a glass rod to control the thickness and uniformity of the membrane. The cast films were dried in a hot, air oven at 405° C for 248 hr to allow solvent evaporation to be slow and uniform, thus ensuring proper film formation [14,15]. After the drying process, the membranes were gently lifted from the casting surface with a spatula

to avoid any mechanical damage. The dried membranes were likewise kept in a desiccator under controlled conditions so that they would not absorb moisture prior to characterization and performance evaluation [16].



Figure 3. Fabrication of biopolymer membrane: (a) homogeneous blending and (b) casting and drying.

RESULTS AND DISCUSSION

FTIR analysis

Figure 4 of the FTIR spectroscopy was used to analyze the chemical interactions and functional groups involved in the watermelon rind biopolymer membrane. The FTIR spectrum of the biopolymer membrane from watermelon rind shows typical absorption peaks at around 3330, 2920, 1735, 1605, and 1030 cm^{-1} . These peaks can be assigned to the O–H stretching vibrations of cellulose and pectin, C–H stretching, C=O stretching of ester and carboxylic groups, asymmetric stretching of carboxylate ions, and C–O–C/C–O stretching vibrations of polysaccharides, respectively. In addition, the FTIR spectra of the prepared membranes display obvious changes in peak intensity, slight changes in peak position, and broadening of the O–H stretching peak after membrane preparation [17]. These changes suggest the presence of strong intermolecular forces between the membrane components. In particular, the broadening and downward shift of the O–H stretching peak indicate the increased hydrogen bonding between the hydroxyl and carboxyl groups of the watermelon rind components and the biopolymer chains. These forces enhance the structural integrity and functional properties of the membrane, thus confirming the successful incorporation of watermelon rind into the biopolymer matrix and its potential use as a selective gas adsorbent in vehicle emission reduction technology.

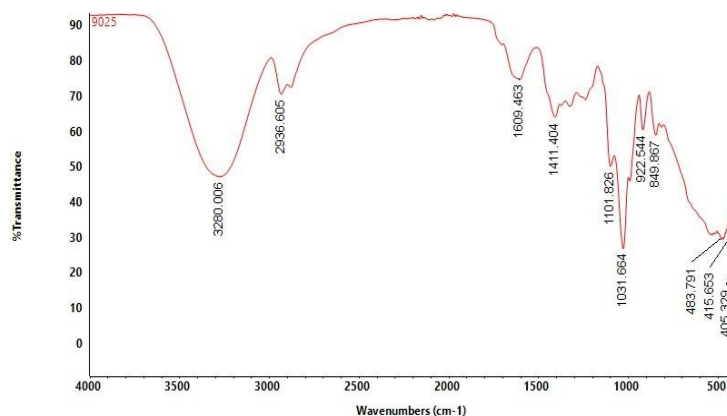


Figure 4. FTIR spectra showing functional groups in the watermelon rind-based membrane.

SEM analysis

The surface morphology of the watermelon rind biopolymer membrane was characterized (Figure 5) by scanning electron microscopy (SEM) along with its structural features. The SEM images reveal that the membrane surface is very smooth and uniform, with a porous network that is evenly spread out throughout. The biopolymer uses from watermelon rind result in the interpenetrating micro-pores and channels, which are the main mechanisms for gas diffusion and selective adsorption. These morphological features are due to the cellulose and pectin components of the watermelon rind, which not only are the natural pore-forming agents but also serve as one source of the biopolymer matrix. In comparison with the pristine biopolymer membrane, the watermelon rind-loaded membrane exhibits improved surface roughness and higher structural compactness; thus, strong interfacial adhesion can be assumed between the rind-derived constituents and the polymer chains. The absence of cracks and phase separation shows that there is good compatibility and homogeneous dispersion of the biopolymer components. Such morphology is perfect for the reduction of targeted vehicle emissions, as the porous yet mechanically stable structure can elevate the pollutant gas trapping capability, thus at the same time membrane integrity is being maintained during the operation [18].

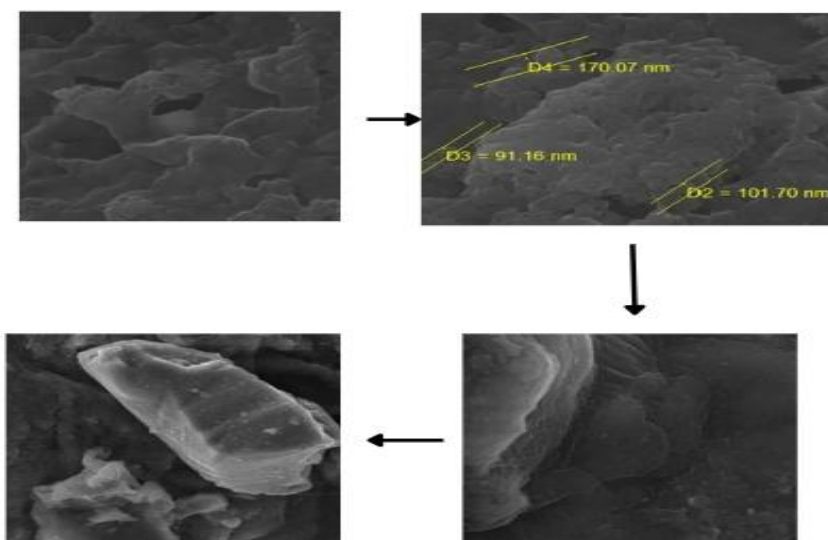


Figure 5. SEM image illustrating surface morphology and porous structure of the membrane.

XRD analysis

Biopolymer membrane derived from watermelon rind was subjected to X-ray diffraction (XRD) (Figure 6) for morphological study, crystalline structure, and phase characteristics. The X-ray diffraction pattern of the biopolymer obtained from the watermelon rind has a broad diffraction peak at around $2\theta = 20-22$, which has been confirmed as a typical semi-crystalline nature of cellulose and pectin extracted from the rind. The broad peak is an indication that the biopolymer matrix contains both amorphous and crystalline regions. After the membrane has been formed, the intensity of the peak is greatly lowered, and the peak is slightly broadened as well; therefore, the decrease of crystallinity is implied. This occurrence can be accounted for by the fact that the intermolecular interactions between the components of the watermelon rind and the biopolymer

chains are so strong that they result in the disruption of the ordered crystalline domains of cellulose. The increased amorphous nature is quite beneficial for membrane applications since it enables gas permeability and adsorption capacity. These results are proof of the effective incorporation of the watermelon rind into the biopolymer network, and they signify its potential for the emission reduction of vehicles by structural flexibility and functional performance enhancement.

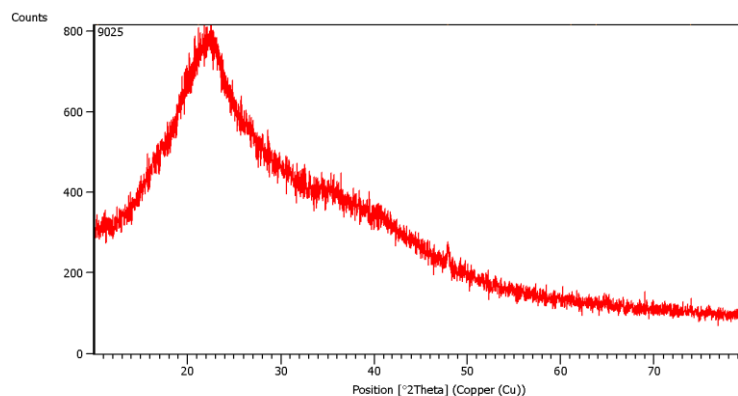


Figure 6. XRD pattern indicating crystalline and amorphous phases of the membrane.

Targeted gas adsorption

The biopolymer membrane fabricated from watermelon rind was evaluated for its gas adsorption performance to assess its capability in capturing vehicular gaseous pollutants (Figure 7). The membrane showed a striking adsorption capacity for the target gases such as CO and NO, which is in essence due to the abundance of hydroxyl, carboxyl, and cellulose-based functional groups originating from the watermelon rind. These surface functional groups facilitate physicochemical interactions like hydrogen bonding and dipole interactions, thus making gas capture more efficient. In addition, the porous microstructure of the biopolymer matrix provides a large surface area and accessible adsorption sites, enabling gas molecules to diffuse and be retained quickly. The adsorption pattern was stable in the repeated cycles; thus, the membrane's reusability and structural integrity were positively confirmed. Hence, the gas adsorption outcomes are a lucid indication that the biopolymer membrane from watermelon rind is a viable material in accordance with the sustainability concept, which can be instrumental in alleviating the impact of vehicular emissions through efficient gas adsorption mechanisms. The membrane is created in order to capture certain emissions from vehicles, namely CO₂, NO_x (including both NO and NO₂), and SO₂/ SO_x. These gases are among the significant sources of air pollution and global warming. The selection of such gases was conducted through the identification and quantification of the gases in the environment, similar to the exhaust gases. Certain concentrations of the target gases were fed into the filtration system, and then the concentration of the gases before and after filtration by the membrane was determined through gas analysis techniques. The existence of hydroxyl and carboxyl groups in cellulose and pectin provides better interactions between the polymer and gaseous pollutants, like CO₂ and SO₂, due to hydrogen bonds and dipole attractions. Likewise, NO_x gases are attracted to the surface reactive sites through physico-chemical adsorption. Although this membrane does not demonstrate the property of molecular selectivity in terms of molecular sieves, the adsorption is selective to gases that react chemically with the functional groups of cellulose and pectin compared to non-reactive gases.

$$Q = \frac{(W_f - W_i)}{W_i} * 100$$

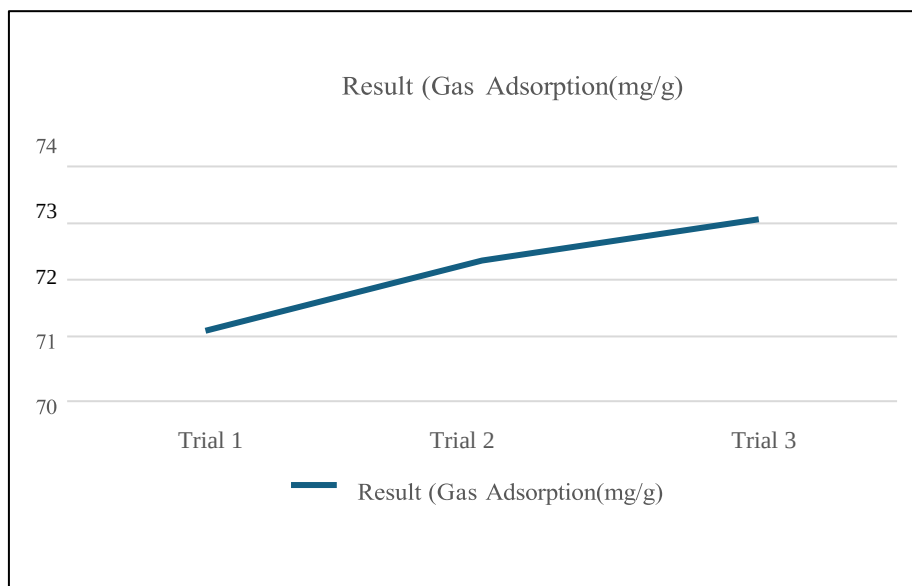


Figure 7. Gas adsorption capacity of the membrane for target pollutants under repeated trials.

Filter efficiency and pressure drop

Filtration performance of the watermelon rind biopolymer membrane was assessed based on filtration efficiency and changes in pressure drop using a lab-scale air filtration test setup. The membrane sample was installed in a sealed filter holder with a certain effective filtration area to prevent air leakage. A controlled airflow containing test particulates was pushed through the membrane at a constant flow rate to simulate filtration conditions. Particle concentrations upstream (C1) and downstream (C2) of the membrane were measured with a particle counter. The filtration efficiency (%) was calculated by the formula (%) = [(C1- C2) / C1] * 100. The pressure drops (P) through the membrane were also recorded at the same time with a differential pressure manometer under similar flow conditions. These measurements made it possible to determine membrane permeability, airflow resistance, and overall filtration performance, which are the major factors in the evaluation of the feasibility of the developed membranes for vehicle emission control applications. This includes the use of well-controlled concentrations of CO₂, NO_x, and gases containing sulphur in an exhaust gas-like environment. The experiment was carried out in a flow of air, where a consistent flow rate and exposure period were maintained to ensure a homogeneous interaction between the gas mixture and the membrane. Gas concentrations before and after the filtration process were determined through standard laboratory analyses, utilizing the appropriate gas analysis instruments for measuring CO₂, NO_x, and SO₂ levels. Furthermore, a description of the laboratory-scale filtration apparatus used has been provided, including all relevant parameters. The hydrophilic properties of cellulose and pectin mean that the membrane will absorb moisture in environments with high humidity. Humidity will thus affect the behavior of the membrane. Moderate humidity will help increase the adsorption activity because it will facilitate the creation of a thin film of water, which helps polar molecules like CO₂ and SO₂ dissolve and interact with the membrane. In high humidity, however, excess moisture may make

the membrane swell, thereby decreasing porosity and pore accessibility. It could also reduce gas diffusivity while causing an increase in pressure drops because of partial clogging of pores. The membrane was tested in the presence of different gases to simulate the actual exhaust environment; however, no particular study has been carried out to analyze the impacts of competitive adsorption. In multicomponent systems, competitive adsorption might take place in which those gases that have high affinities (such as CO₂ and SO₂ because of their polarity and solubility) tend to get adsorbed onto the active sites, thus limiting the adsorption capacity of other gases (for instance, NO_x).

$$\text{Efficiency} = \frac{(C_1 - C_2)}{C_1} * 100$$

Pressure drops

$$\Delta P \text{ (kPa)} = P_1 - P_2$$

Bubble point and capillary porometry

The watermelon rind-derived biopolymer membranes that were deliberately fabricated were assessed for their pore structure characteristics by bubble point and capillary flow porometry methods (Figure 8). Fragments of the membrane were thoroughly wetted with a low surface tension wetting liquid to ensure that the pores were completely filled. The wetted membrane was placed in the porometer sample holder and subjected to gradually increasing gas pressure. The bubble point pressure, i.e., the pressure at which the largest pore is freed from the liquid, was recorded. From this value, the maximum pore size of the membrane was calculated. Subsequently, capillary flow porometry was carried out with pressure being increased stepwise to empty the smaller pores so that the mean flow pore size and pore size distribution could be obtained. The pore diameter D was obtained from the Laplace equation, $D = 4\cos$, where represents the surface tension of the wetting liquid, is the contact angle, and P is the applied pressure. These measurements gave quantitative data on the membrane pore structure that had a significant impact on filtration efficiency and airflow resistance.

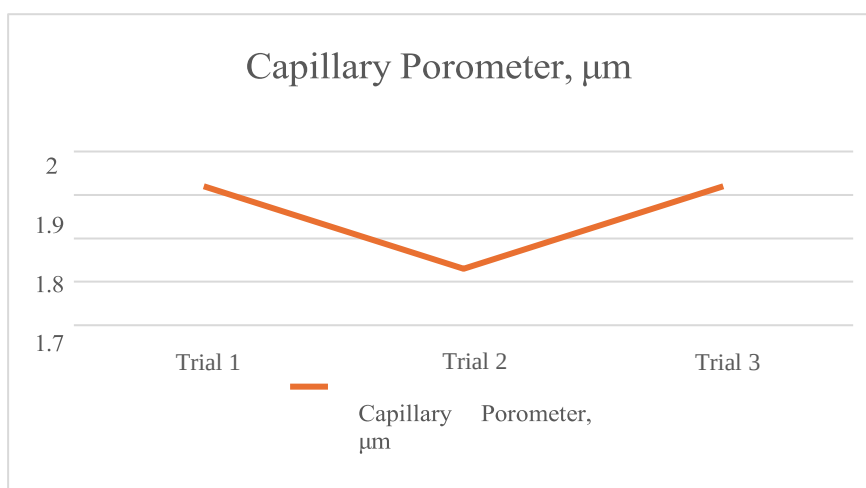


Figure 8. Pore size distribution and airflow analysis using capillary flow porometry.

Thermogravimetric analysis

Thermogravimetric analysis (TGA) was used to assess the thermal stability of biopolymer membranes isolated from watermelon rind (Figure 9). A piece of membrane weighing 5 to 10 mg was placed in a platinum crucible and heated from room temperature to 600 °C to 800 °C at a constant heating rate of 10 min under a nitrogen atmosphere to prevent oxidative degradation. The change in weight was recorded as a function of temperature to assess the thermal degradation behavior. The very first loss of weight at low temperatures was caused by the evaporation of physically adsorbed moisture, while the major stages of weight loss were associated with the thermal decomposition of biopolymer components such as cellulose, hemicellulose, and residual organic components. The residual char content at higher temperatures represented the thermal resistance and the structural stability of the membrane. The TGA results were the basis for safety determinations of the membranes at elevated temperatures, e.g., vehicle exhaust filtration systems. The TGA test was performed at a very wide temperature interval of 600–800 °C in order to analyze the complete pattern of thermal degradation and material stability. The application of the material will be in the moderate exhaust temperature regime of 100–400 °C. It is therefore clarified that thermal decomposition does not occur at such temperatures and that the material is thus suitable for its practical application. Another important advantage gained from performing TGA at higher temperatures is that it ensures extra security, in case the exhaust temperature rises above 400 °C.

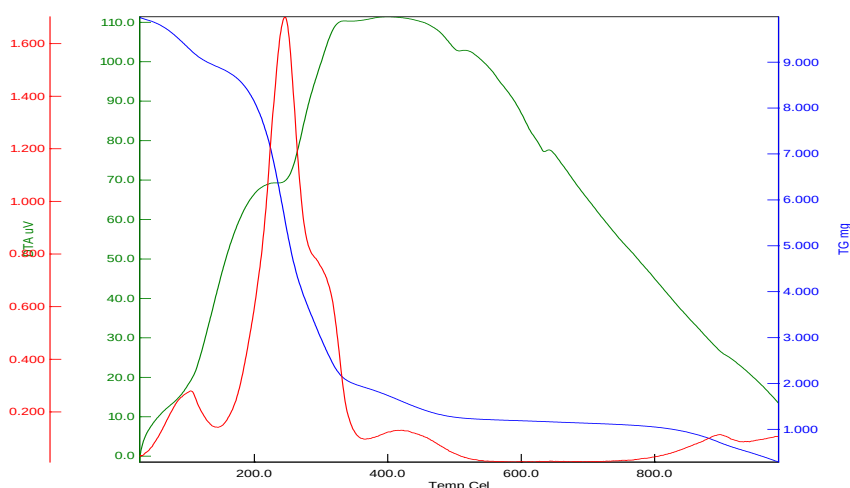


Figure 9. Thermogravimetric analysis showing thermal stability and degradation behavior of the membrane.

Reusability cycle and dust holding capacity

Figure 10 shows one of the methods to know membrane life and its stability over time was to take the watermelon rind-based biopolymer membrane through several filtration and regeneration cycles. After every filtration cycle, the membrane needed to be removed from the holder and washed with distilled water and a mild ethanol solution to remove the particulates and contaminants, which were adsorbed and deposited. After that, the membranes were again dried at 40–50 °C until the weight stayed constant before being reused. It was decided that such filtration, regeneration treatment would only be done for a few cycles (usually 5, 10 cycles). Under the same

experimental conditions, filtration efficiency and pressure drop were determined after each cycle. The extent to which the performance parameters were maintained was considered a measure of membrane stability and reusability. Hence, if the membrane can retain at least 80, 90% of its original filtration efficiency while only having a minimal increase in pressure drop, then it is regarded as reusable. The reusability test results reveal the mechanical strength, resistance to fouling, and the potential of the fabricated membranes for long-term vehicle emission control and air filtration applications. The dust holding capacity of a biopolymer membrane from watermelon rind was determined through continuous filtration. The filter was subjected to dust; thus, the air flow of a known volume was maintained under controlled conditions until the terminal pressure drop was detected. The difference in the filter weight before and after the dust loading was used to determine the amount of the entrapped particle. It was found that the filter had a good dust-holding capacity, such that it could retain particles and thus was characterized by slow clogging of the pores. The main reason for such performance is that the filter has a 3D porous network structure with abundant surface functional groups, which facilitate particle adhesion and, consequently, the buildup of particles within the filter matrix. The filter dust holding capacity was quite sufficient that it can be used for a long-term filtration operation, thus there will be less frequent maintenance work, and the replacement of the membrane for the emission control purpose will be the practical scenario. The efficiency of filtration remained around 80-90% even after multiple uses, suggesting the mechanical stability of the membranes. It has been observed that adding PVA to the membrane improved its flexibility and mechanical robustness. Although mechanical characterization might give us better results.

$$\text{DHC} = \frac{W_1 - W_0}{A}$$

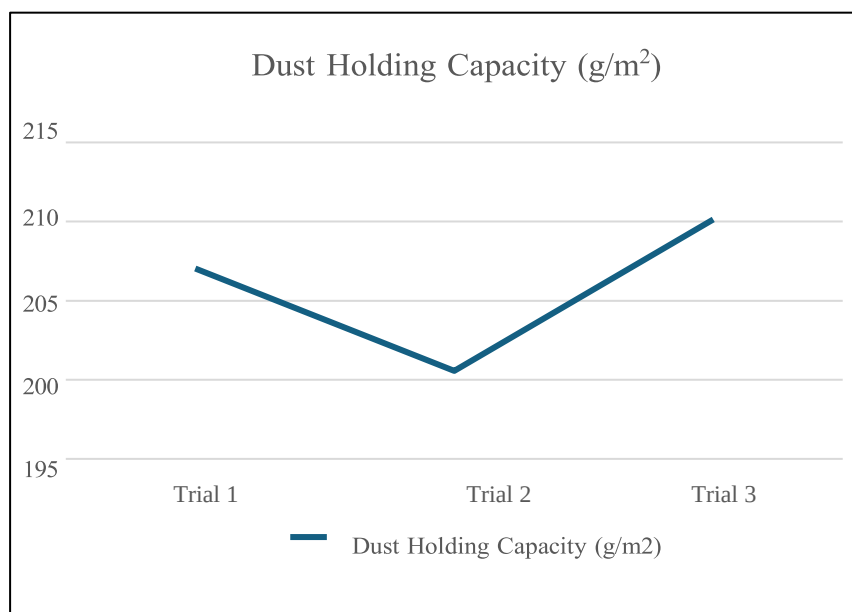


Figure 10. Reusability and dust holding capacity of the membrane during filtration cycles.

Performance comparison between membranes having and not having PVA

Performance of membranes made of either type can be compared to identify the importance of using PVA in membrane formation. The absence of PVA results in poor mechanical stability and

makes the membranes fragile, while the usage of PVA provides flexibility and mechanical strength due to reinforcement of polymer chains. As far as morphology is concerned, the porosity of membranes without PVA can be considered moderate, whereas the addition of PVA improves morphology and provides well-developed pores due to the better compatibility of phases. Regarding adsorption capabilities, gas adsorption in membranes not containing PVA is moderate; however, PVA addition raises their capacity to high values due to a greater number of active sites and enhanced interaction between the gas molecules and polymer matrix. What is important is that membranes produced without PVA cannot be used repeatedly more than one or two times; in contrast, those containing PVA have proven stable for up to 5-10 cycles. Moreover, filtration efficiency increases up to 85% when PVA is present due to enhanced adsorption capacity and gas flow paths.

CONCLUSION

In a biopolymer membrane from watermelon rind, which is a renewable agricultural waste material. Our pretreatment and blending methods effectively removed non-cellulosic components. This allowed us to develop membranes that are both mechanically stable and flexible. FTIR analysis showed that the membranes contained many hydroxyl and carboxyl functional groups. This confirmed a successful interaction between the biopolymers in the watermelon rind and polyvinyl alcohol, which is important for improving gas adsorption and filtration performance. The XRD results showed that the membranes had a semi-crystalline structure. This indicated better cellulose ordering after pretreatment and compatibility between the biopolymer from the rind and the PVA matrix. SEM micrographs displayed a uniform surface with an interconnected porous structure. This design helps capture particles efficiently while keeping airflow resistance manageable. These structural and chemical features directly influenced the filtration performance we observed. Measurements of filtration efficiency and pressure drop showed that the membranes effectively remove pollutants while maintaining acceptable airflow resistance. We used bubble point and capillary flow porometry analyses to confirm a suitable pore size distribution for air filtration applications. Additionally, thermogravimetric analysis indicated enough thermal stability at moderate temperatures, which are relevant for vehicular exhaust systems. Overall, this study demonstrates the potential of watermelon rind-based biopolymer membranes as eco-friendly, low-cost alternatives to traditional synthetic filters. This supports sustainable emission control and environmental solutions based on a circular economy. The prepared watermelon rind-based membrane is more effective than existing cellulose/pectin or PVA-based membranes because of its synergic blend and improved functionality. For instance, the blend of cellulose, pectin, and PVA results in many hydroxyl and carboxyl functional groups that can absorb and remove CO₂, NO_x, and sulfur pollutants with an effectiveness of up to 85%. Besides, the presence of PVA makes the membrane flexible, tough, and durable to overcome the brittleness problem of traditional pure biopolymers. Furthermore, from the practical point of view, this membrane can be used for multiple filtration operations as it maintains about 80–90% of its efficiency while having moderate pressure drop and dust holding capacity. In addition to that, the use of agro-waste like melon peels at very economical prices makes it sustainable and scalable, making it suitable for the circular economy concept. All these attributes indicate that the fabricated membrane is efficient, robust, and practical.

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Authors' contributions

Sasireka Gunasekaran: Project Administration, Conception, Supervision, Jamesraj Sathish: Writing and Drafting, Resources, Ramasamy Palani: Critical Review and Revision, Saran Geethan Lingam: Data Acquisition, Data Analysis, Methodology.

*Ethical approval**

This is not applicable

*Consent to participate**

This is not applicable

*Consent to publish**

This is not applicable

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement

Data is available on request

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